PROGRESS IN PERTURBATIVE COLOR TRANSPARENCY

John P. Ralston[a], Pankaj Jain[b], Bijoy Kundu[c], Jim Samuelsson[d]

[a]*Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA*
Email: ralston@ukans.edu
[b]*Department of Physics, IIT Kanpur, Kanpur-208 016, India*
E-mail: pkjain@iitk.ac.in
[c]*Department of Physics, University of Virginia, Charlottesville VA, USA*
E-mail: bkundu@jlab.org
[d]*Department of Theoretical Physics, University of Lund , Lund S-22362, Sweden*
E-mail: jim@thep.lu.se

Abstract. A brief overview of the status of color transparency experiments is presented. We report on the first complete calculations of color transparency within a perturbative QCD framework. We also comment on the underlying factorization method and assumptions. Detailed calculations show that the slope of the transparency ratio with Q^2, and the effective attenuation cross sections extracted from color transparency experiments depend on the x distribuition of wave functions.

I   OVERVIEW

Several experiments indicate that color transparency [1] and nuclear filtering [2–4] have been observed at large nuclear number A. The first color transparency experiment of Carroll *et al* [5] convincingly showed that interference effects in proton-proton scattering were filtered away in nuclear targets. Fits to the attenuation cross section in nuclear targets show values significantly below the Glauber theory values [6]. The FNAL E-665 experiment [7] also proved consistent with filtering effects [8]. The observation of increasing longitudinal final state polarization in $\gamma^* A \to \rho A$ as a function of Q^2 is noteworthy. We still await confirmation of predicted longitudinal polarization increasing as a function of A [4].

Electron beam experiments remain controversial, with few signals of interesting Q^2 dependence [9]. A basic feature of γ^*-initiated reactions is that most events are knocked out from the back side of the nucleus. This minimizes the resolving power of such experiments to measure the size of propagating states. The A dependence is a particularly useful tool [6] to measure effective attenuation cross sections. O'Neill *et al* [10] showed that effective attenuation cross sections extracted from $A(e, e'p)$

SLAC data were smaller than Glauber theory calculations by a statistically significant amount. However, the precision of the data [9] was insufficient to establish a large effect, and model dependence in the choice of the normalization of hard scattering is another complication. Reports on new $(e, e'p)$ beam experiments from CEBAF are expected shortly.

Progress on the theory front has come from looking deeper at the basic factorization methods [3], and doing the work of labor-intensive calculations [11]. The asymptotic factorization scheme of Lepage and Brodsky [12] is inadequate. An integration over the transverse separation of quarks is needed in the description. We call this "impact parameter factorization", which is needed to describe the interactions with the nuclear target, which otherwise vanish prematurely in the pure short-distance scheme. The impact parameter method was originally found necessary to regulate Landshoff and Sudakov effects in pp scattering [13]. We adapted it to describe color transparency and nuclear filtering [3,11]. Impact-parameter factorization has subsequently become very popular for the description of free-space form factors [14,15], which remain controversial [16,17] at laboratory Q^2 values.

II THE CALCULATIONS

Elsewhere [11] we report details of calculations of hard-pion knockout, $\gamma^* A \to \pi A'$, and hard nucleon knockout, $\gamma^* A \to p A'$. These are exploratory concept studies, designed to see how $pQCD$ predicts color transparency and filtering with few parameters. Since all the details except for experimental acceptances have been incorporated, the calculations are also fully quantitative predictions of the type needed to compare to experiments.

The case of pionic transparency deserves special mention. First, the pion is the cleanest theoretical laboratory one would desire. A short-distance wave function is known from experiments on pion decay , without relying on the sometimes circular logic of schemes such as QCD sum rules. Second, a pion is ultra-relativistic at energies as low as a few GeV. This helps strengthen the approximations made in $pQCD$. Finally, the pion has only two quarks in its valence state, and one transverse separation b, reducing the complexity of the calculations.

Working in configuration (impact-parameter b) space the expression for a $\gamma^* - meson$ form-factor becomes:

$$F_\pi(Q^2) = \int dx_1 dx_2 \frac{d^2\vec{b}}{(2\pi)^2} \mathcal{P}(x_2, b, P_2, \mu) \tilde{H}(x_1, x_2, Q^2, \vec{b}, \mu) \mathcal{P}(x_1, b, P_1, \mu). \quad (1)$$

Here $\mathcal{P}(x, b, P, \mu)$ represent the Fourier transforms of the wave functions, including Sudakov factors; $\tilde{H}(x_1, x_2, Q^2, \vec{b}, \mu)$ represents the hard scattering kernel from perturbation theory. The impact parameter $\vec{b}$ is conjugate to $\vec{k}_{T1} - \vec{k}_{T2}$, μ is the renormalization scale, and P_1, P_2 are the initial and final momenta of the meson.

The nuclear medium modifies the quark wave function by an interaction kernel f_A, which is called the nuclear filtering amplitude. An eikonal form [3] appropriate

for f_A is: $f_A(b; B) = exp(-\int_z^\infty dz'\sigma(b)\rho(B, z')/2)$. Here $\rho(B, z')$ is the nuclear number density at longitudinal distance z' and impact parameter B relative to the nuclear center. We parametrize $\sigma(b)$ as kb^2 for our calculations. Finally, we must include the probability to find a target at position B, z inside the nucleus. Then the wave functions $\mathcal{P}_A$ appropriate for the nuclear target are [3]

$$\mathcal{P}_A(x, b, P, \mu) = f_A(b; B)\mathcal{P}(x, b, P, \mu).$$

Putting together the factors, the process of knocking out a hadron from inside a nuclear target has an amplitude M given by

$$M = \int_0^\infty d^2B(\Pi dx_i d^2b_i) \int_{-\infty}^{+\infty} dz\rho(B, z) \times F_\pi(x_1, x_2, b, Q^2) \times f_A(b, B) \qquad (2)$$

The analysis for the proton is similar but vastly more complicated. A 9 dimensional integration over the various x_i, b_i coordinates is performed by Monte Carlo. Sudakov effects are set to depend on the maximum of the three quark separation distances, $b_{max} = max(b_1, b_2, b_3)$.

We find that the physics is not described by a free-space hard scattering, followed by some model of propagation with or without "expansion", which is the ansatz of most competing groups. The integrations over the transverse quark variable extend over the whole volume of the nucleus. There is no easy decoupling into a simple product of "hard" times "nuclear" effects. Color transparency truly probes the internal structure of hadrons.

We found uncertainties in the nuclear correlations at the 10% level to be a major concern, in some cases exceeding the theoretical uncertainties from the rest of the calculation [11]. Primary new results include a discovery that the *slope* of the transparency ratio with Q^2 depends strongly on the $x-$ dependence of wave functions (distribution amplitudes). This mysterious effect was traced to the fact that central wave functions are more effective in maintaining short distance. Endpoint dominated distributions tend to exacerbate long-distance effects, which are found not to produce transparency. Nuclear filtering was observed to depend on the choice of wave functions as consistent. Thus both the slope of transparency ratios, and the magnitude of effective attenuation cross sections extracted from data, are probes of $x-$ dependence. Extensive details and nearly a dozen plots are given in Ref. [11].

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